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Properties of High-Latitude CME-Driven Disturbances During Ulysses Second Northern Polar Passage

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[1] Ulysses observed five coronal mass ejections (CMEs) and their associated disturbances while the spacecraft was immersed in the polar coronal hole (CH) flow above 70° N in late 2001. Of these CMEs, two were very fast (>850 km s^{-1}) driving strong shocks in the wind ahead, and two others were over-expanding. The two fast CMEs were observed leaving the Sun by LASCO/SOHO, and were observed in the ecliptic by Genesis and ACE. These were large events, spanning at least from the northern heliospheric pole to the ecliptic. One-dimensional hydrodynamic simulations indicate that these could be described as overpressured CMEs launched from the Sun at speeds initially faster than ambient, but then decelerating to the ambient solar wind speed as they propagated outward. The two over-expanding CMEs mark their first occurrence since Ulysses' first orbit when such CMEs were only observed in polar CH flow. *INDEX TERMS:* 7513 Solar Physics, Astrophysics, and Astronomy: Coronal mass ejections; 2164 Interplanetary Physics: Solar wind plasma; 2162 Interplanetary Physics: Solar cycle variations (7536). **Citation:** Reisenfeld, D. B., J. T. Gosling, R. J. Forsyth, P. Riley, and O. C. St. Cyr, Properties of high-latitude CME-driven disturbances during Ulysses second northern polar passage, *Geophys. Res. Lett.*, *30*(19), 8031, doi:10.1029/2003GL017155, 2003.

1. Introduction

[2] Coronal mass ejections (CMEs) are transient events in which large amounts of solar plasma erupt into interplanetary space, a result of the opening of previously magnetically closed regions in the solar atmosphere [e. g., *Rust et al.*, 1980]. Space-born coronagraphs have observed the eruption of CMEs from all latitudes of the Sun, but until Ulysses began its first polar orbit in 1992, in situ observations of CMEs had only been made in the ecliptic. During Ulysses first polar orbit, six CMEs were observed at heliolatitudes above 33° when Ulysses was immersed in the fast (>700 km s^{-1}), steady polar coronal hole (CH) flow of solar minimum.

[3] These events all had high speeds, with an overall average speed of 710 km s^{-1}, compared to low latitude CMEs which have an average speed of ~400 km s^{-1} [*Gosling et al.*, 1994]. The Ulysses observations also led to the discovery of a new class of CMEs, coined "over-expanding" CMEs, where an initially high internal pressure (rather than a speed difference between the ejecta and the surrounding solar wind) often produces forward and/or reverse shocks that propagate into the ambient solar wind and deep pressure rarefactions within the CMEs themselves [*Gosling et al.*, 1994, 1998]. Of the six observed high-latitude CMEs, all but one was classified as over-expanding.

[4] Ulysses recently completed its second polar orbit, occurring around solar maximum. During the southern polar pass, Ulysses encountered highly variable solar wind, comparable to what is commonly observed in the ecliptic. CMEs were observed up to the highest latitude of Ulysses orbit, 80° S. The CMEs themselves showed no qualities that distinguished them from low-latitude CMEs.

[5] The northern polar pass of Ulysses' second orbit occurred just after solar maximum when a new polar CH had formed over the North Pole above 70° N [*McComas et al.*, 2002]. During this period, between September and November 2001, Ulysses intercepted five CMEs, all of which were embedded in otherwise relatively unstructured flow at a steady speed of ~700 km s^{-1}, quite similar to the steady unstructured flow observed during Ulysses' first polar orbit. Two of the five observed CMEs were over-expanding. This marks their first occurrence in the Ulysses observations since the first orbit. The other three CMEs were unlike any of those observed in the polar CH flow of the first polar orbit. Two were very fast CMEs (>850 km s^{-1}) driving strong shocks in the wind ahead, and the third was a magnetic cloud nearly in equilibrium with the ambient wind. The two fast CME were remarkable in that they were also observed in the ecliptic by solar wind instruments at 1 AU. Additionally, because Ulysses was positioned almost directly above the Sun's north limb at this time, we were able to associate this pair of CMEs with coronal eruptions observed by the LASCO experiment on SOHO [*Brueckner et al.*, 1995].

[6] Here, we present and discuss two of the five CME-driven events observed by Ulysses while it was immersed in the northern polar CH. We first present the over-expanding CME observed on September 27–29, 2001. This is the first

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over-expanding CME observed since 1996 and we wish to document how it compares to those observed during the first orbit. We then concentrate particular attention on one of the two fast CMEs, observed by Ulysses on November 8–11, 2001. In addition to its large extent, this event exhibits unique dynamic properties not previously observed in high-latitude CMEs. To understand these properties better, we have used the LASCO observations to determine the initial launch time and speed of the CME, and then used this as an input into a one-dimensional hydrodynamic (1–D HD) model of CME evolution.

2. CME Observations

[7] We present here high-latitude plasma and field observations made by the Ulysses ion and electron spectrometers [*Bame et al.*, 1992], and magnetometer [*Balogh et al.*, 1992]. For the November 8–11 CME, we also present in-ecliptic plasma observations made by the Genesis ion monitor [*Barraclough et al.*, 2003], the ACE electron spectrometer [*McComas et al.*, 1998] and magnetometer [*Smith et al.*, 1998]. Shocks were identified in the data as simultaneous discontinuous transitions in the speed, density, temperature, and magnetic field. We determined that these were fast mode shocks by verifying that each had a propagation speed faster than the upstream magnetosonic speed.

2.1. September 27–30, 2001 Event

[8] An over-expanding CME was observed by Ulysses at 1.9 AU and 78° N on September 27–30, 2001. This is the first of two over-expanding CMEs observed during the northern coronal hole crossing; the second was observed on October 29–November 1, 2001 and is discussed elsewhere [*Reisenfeld et al.*, 2003]. Although we have attempted to identify a LASCO counterpart for the September 27–30 event, there was too much activity in the corona at this time to identify the source unambiguously. Figure 1 shows the plasma and field parameters for the event. We identify the CME by the presence of intermittent counter-streaming halo electrons, a preceding forward shock and a trailing reverse shock, a depressed proton temperature, and a low variance magnetic field.

[9] This event appears quite similar to the July 20–26, 1993 CME disturbance observed at 4.5 AU and 35° S during the first polar orbit, and described in *Gosling and Riley* [1996]. For that event, the authors performed 1–D HD simulations, and they found that by initiating the CME at the inner boundary of the simulation (0.14 AU) as a combination of a pressure pulse and a velocity decrease, they could reproduce the observed CME shape. That simulation allows us to understand the evolution of the September 27–30, 2001 CME disturbance. We believe this event originated as a CME leaving the Sun slower and at a greater internal pressure than the ambient wind. The CME was then accelerated up to a higher speed by its interaction with the high-speed CH flow ahead and behind. Although the wind ahead was traveling faster than the center of the CME and at about the same speed as the leading edge of the CME, the internal pressure of the CME was sufficiently strong to drive a forward shock that propagated into the upstream wind. At the rear of the event, a forward wave/reverse shock pair formed due to the trailing high-speed flow overtaking the CME. The expected reverse wave associated with over-expansion of the CME was essentially obliterated by its interaction with the forward wave, which, in turn, probably would have been a forward shock in the absence of its interaction with the reverse wave.

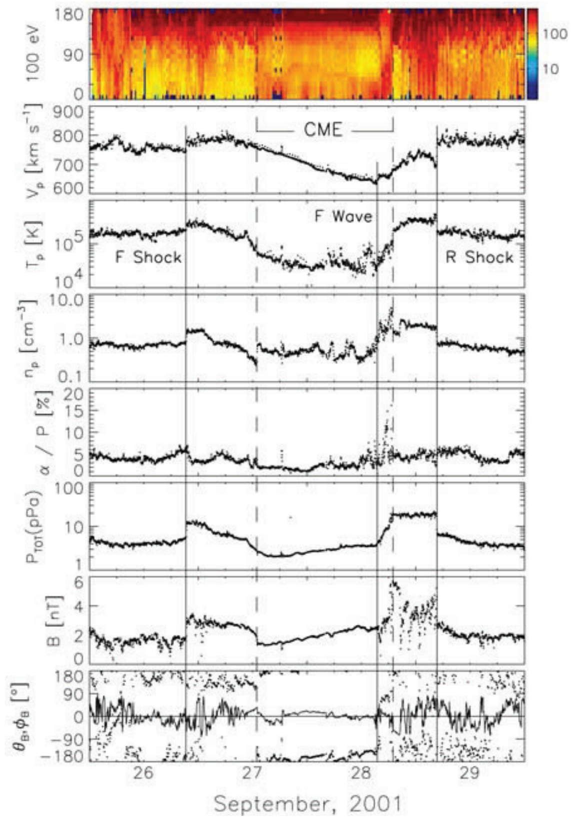

Figure 1. Ulysses plasma and magnetic field data showing a solar wind disturbance driven by an over-expanding CME on September 27–30, 2001. The color-coded top panel shows a pitch angle plot of the suprathermal electron distribution (units of 10^{-30} s^{3}cm^{-6}) as a function of time. Note that the electron pitch angle plot is partially contaminated by a light leak in the instrument, which produced the faint streak between 30° and 60° pitch angle. The next three panels show the proton speed, temperature and density. Next to follow is the total pressure P_{tot}, which is the sum of the plasma (proton, alpha particle, and electron) pressures and the magnetic field pressure. The last two panels show the magnetic field magnitude and the field direction, respectively. The field angles are in an RTN coordinate frame: θ_B (solid line) ranges from −90° to 90° and is the polar angle out of the R–T plane, where positive angles are directed northward; ϕ_B (points) ranges from −180° to 180° and is the azimuthal angle in the R–T plane, where 0° is the anti-sunward direction.

2.2. November 8–11, 2001 Event

[10] We next report a remarkable CME-driven disturbance observed at 77° N and 2.2 AU by Ulysses on November 8–11 and in the ecliptic at 1 AU by the Genesis and ACE spacecraft on November 6–9. We have associated the CME with a large X1 class flare located at N06W18 that was observed by the Sacramento Peak Observatory at 16:35 UT on November 4, 2001. The flare coincided with the eruption of a halo CME observed by LASCO. The CME initiated at a

very fast speed; the projected speed of the CME toward Ulysses was 1450 km s^{-1}. The event also generated type II radio emission observed by both the Ulysses URAP and the Wind WAVES instruments. This event can be traced in the URAP data to a forward shock that arrived at Ulysses on November 8 at 06:50 UT [R. MacDowall, private communication]. At this time, the separation between Ulysses and Earth was 73° in heliolatitude and 64° in heliolongitude. Thus, this was a very large event, spanning at least from the ecliptic to the northern heliospheric pole and, based on the LASCO images, probably deep into southern heliolatitudes.

[11] Figure 2 shows the Ulysses plasma and field data for the November 8–11 event. We identify the CME by the presence of counter-streaming, a very strong forward shock having a strength (n_1/n_2) of 3.3, and a significant helium enhancement of >10% (not shown). With the exception of the compressed leading portion of the CME, the field magnitude within the CME was not particularly high. However, there was gradual field rotation, indicating a flux rope, and the field variance was low. There was also deep density depression in the center of the CME. The event ended with a weak reverse shock propagating into trailing solar wind. Thus, whereas the front half of the event was typical of a fast CME plowing into slower wind ahead, the rear half of the event had the shape of a disturbance associated with an over-expanding CME.

[12] In order to generate a coherent picture of the event from the solar and heliospheric observations, we have performed a 1–D HD simulation of the CME evolution through interplanetary space. Simulations of this sort have been performed in the past to model the evolution of the solar wind in general and CMEs in particular as they propagate through the heliosphere [e. g., *Gosling et al.*, 1998; *Hundhausen*, 1985], but here we use SOHO observations to constrain partially the simulations by providing an initial start time and speed. The calculation was initiated at an inner boundary of 0.14 AU, well outside the critical point where the solar wind becomes supersonic. We introduced the disturbance as a saw-tooth velocity pulse, rising rapidly to 1400 km s^{-1} and tailing off over 10 hours, and a bell-shaped density pulse of 8 times the ambient density initiated at the midpoint of the velocity pulse, lasting 5 hours.

[13] In Figure 2, we overlay the computed speed, density and pressure on the observed plasma profiles. In general, a 1–D simulation predicts too strong an interaction between the CME and the ambient solar wind because it does not incorporate shear flows, which relieve pressure stresses. For example, at the leading edge compression, the simulation generates not only a forward shock, but also a reverse shock that is not observed. The code also neglects magnetic forces. A consequence of this is that simulated pressure waves propagate at the sound speed rather than the magnetosonic speed; thus, the CME-driven disturbance expands less rapidly than what is observed.

[14] Despite these limitations, our simulation has produced an event profile that is qualitatively similar to the disturbance observed at Ulysses. The simulated and observed forward shocks arrive at Ulysses at almost exactly the same time. The model speed immediately downstream of the forward shock is quite close to the observed speed, and the density depressions are also well matched. In addition, a small reverse shock is generated at the rear of the simulated event due to the high density within the initial

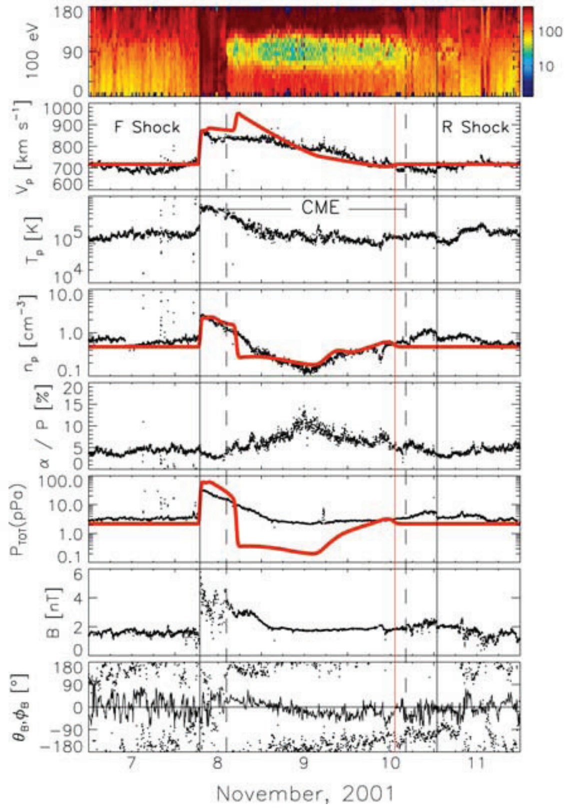

Figure 2. Ulysses plasma and magnetic field data showing a solar wind disturbance driven by a fast CME on November 7–11, 2001. The CME is shown between the dashed lines. See Figure 1 for an explanation of panels. In the panels for the speed, density and total pressure, the solid red curves show the results from the 1-D HD simulation of the event. The vertical red line denotes the reverse shock in the simulation.

CME, also in agreement with the observations. Note that it is important that the initial density pulse lag the velocity peak. The trailing reverse shock does not appear if we introduce a velocity pulse alone, nor does it appear if the density pulse completely overlaps the velocity pulse and does not lag it. The physical rational for a lagging density pulse might be a filament eruption in which an overlying eruption drags out denser filament material below it.

[15] The in-ecliptic counterpart to the Ulysses November 8–11 event was observed at 1 AU on November 6–9. The CME was preceded by a powerful solar energetic particle event that saturated the ACE ion and electron plasma sensors until well into the CME; however, data from the Genesis ion monitor was unaffected. Thus, we have combined ion observations from Genesis with electron and field observations from ACE, shown in Figure 3.

[16] The overall event profile is typical for a fast CME propagating through a slower ambient solar wind. The evolution of the disturbance is dominated by the pressure gradients that develop in response to the relative motion between the CME and the ambient solar wind. A forward shock forms at the compression front produced by the fast CME overtaking slower solar wind upstream, and the rear of the event expands as the CME pulls away from the trailing plasma. This phenomenon has been demonstrated

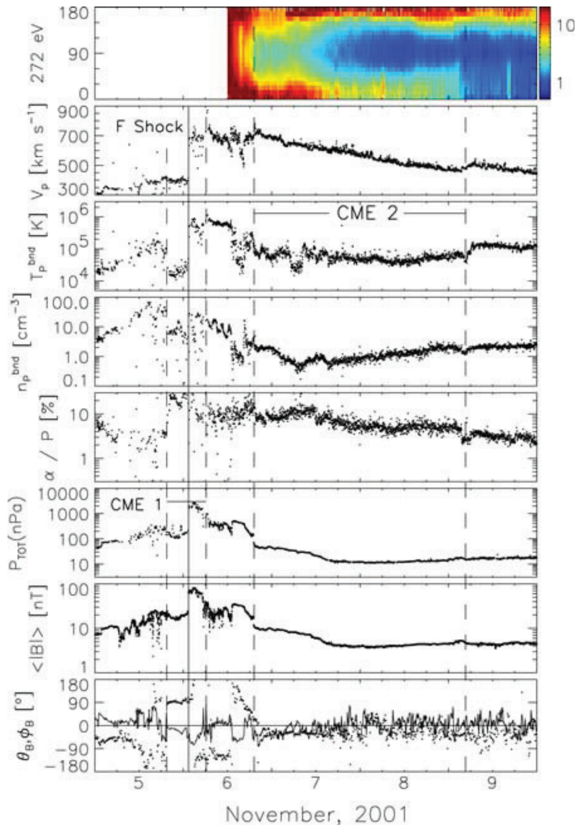

Figure 3. Genesis ion and ACE electron and magnetic field data showing a solar wind disturbance driven by a fast CME on November 5–9, 2001. Two CMEs are present. The first (CME 1) was being overtaken by the forward shock leading the second (CME 2). See Figure 1 for explanation of panels.

by previous HD simulations [e. g., *Hundhausen*, 1985] and will not be reproduced here.

[17] Although CMEs have been simultaneously observed by separated spacecraft in the past [e. g., *Burlaga et al.*, 1981], to the best of our knowledge, no CME has ever been simultaneously detected before by spacecraft with such a large separation, particularly in latitude. Interestingly, this event turns out not to be unique. Ulysses observed a second fast CME on November 26–29, 2001, having a very similar profile. This event was observed leaving the Sun by LASCO on November 22, and it was observed in the ecliptic at 1 AU [*Reisenfeld et al.*, 2003].

3. Conclusions

[18] We have described Ulysses observations of two CMEs, both observed above 75° N, in the northern polar coronal hole that developed just after the maximum of the present solar cycle. The CMEs that Ulysses encountered exhibited much more variety than those observed during the spacecraft's first orbit. The second orbit observations confirm that over-expanding CMEs are common in the high-speed wind of polar coronal holes. To our knowledge, they have never been observed in the ecliptic, but this new set of observations at high latitudes shows their presence during the first orbit was not a unique occurrence. However, unlike the first orbit, the evolution of only two of the CMEs was dominated by over-expansion. The other three were quite different, and in particular, two of them were driven by very high speeds. This is probably a reflection of the greater overall activity of the Sun near solar maximum.

[19] We also see evidence that CMEs propagate to high latitudes in the heliosphere. This is likely the case for the November 8–11 event, which is clearly associated with an active region close to the terrestrial subsolar point. Furthermore, 2–D and 3–D HD simulations by *Riley et al.* [1999] and *Odstrcil and Pizzo* [1999] show that CME-driven disturbances can undergo significant lateral expansion in the heliosphere, with most of the expansion occurring near the Sun. Based on these simulations, it is reasonable to expect that CMEs launched near active regions at lower latitudes may expand in the heliosphere and extend to high latitudes where they are observed by Ulysses.

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